From installation to integration: phase transitions in Advanced

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for the LIGO Scientific Collaboration

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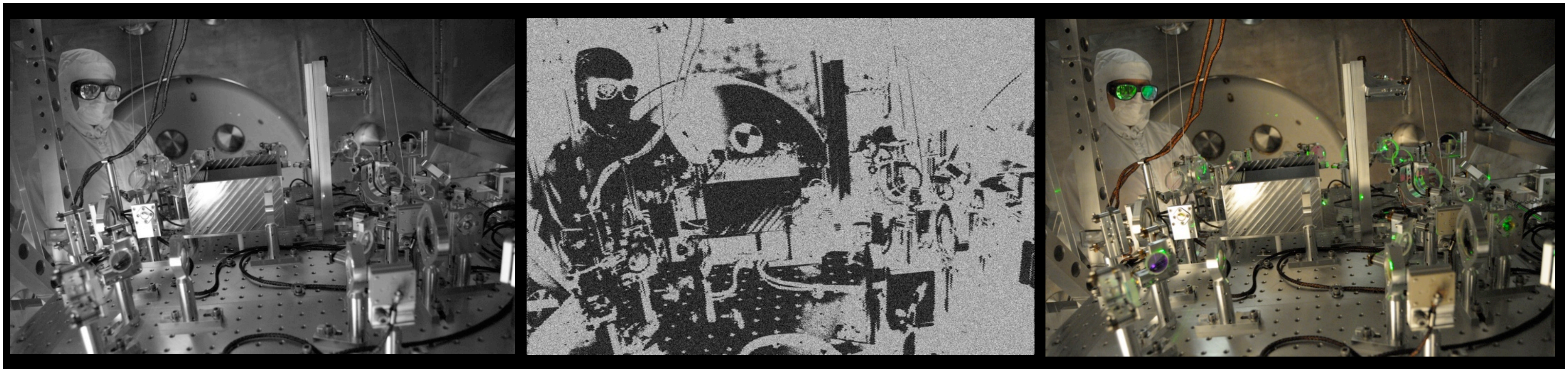
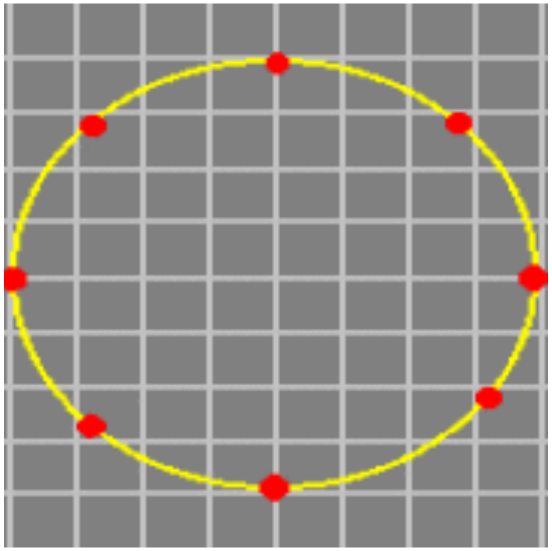


Outline

- Introduction to Advanced LIGO
  - » Gravitational waves
  - » Advanced LIGO design
- Installation status
- Integration status
  - » LIGO Livingston: Dual-recycled Michelson (*DRMI*)
  - » LIGO Hanford: Half-interferometer (*HIFO*)
- Science with Advanced LIGO
  - » Expected NS-NS merger rates
  - » Early science run scenario
  - » LIGO India

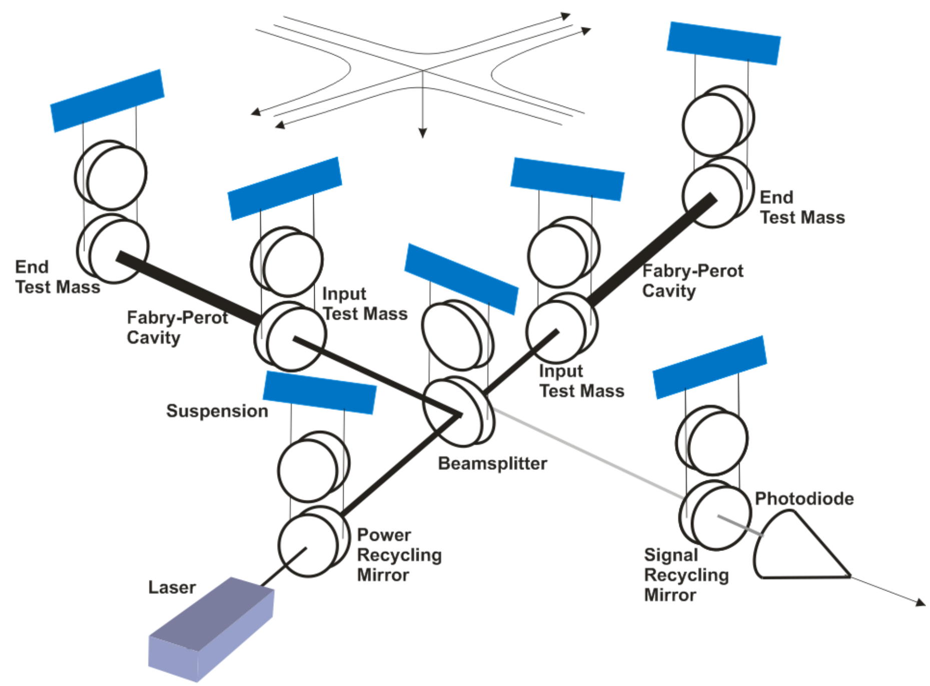
Gravitational waves

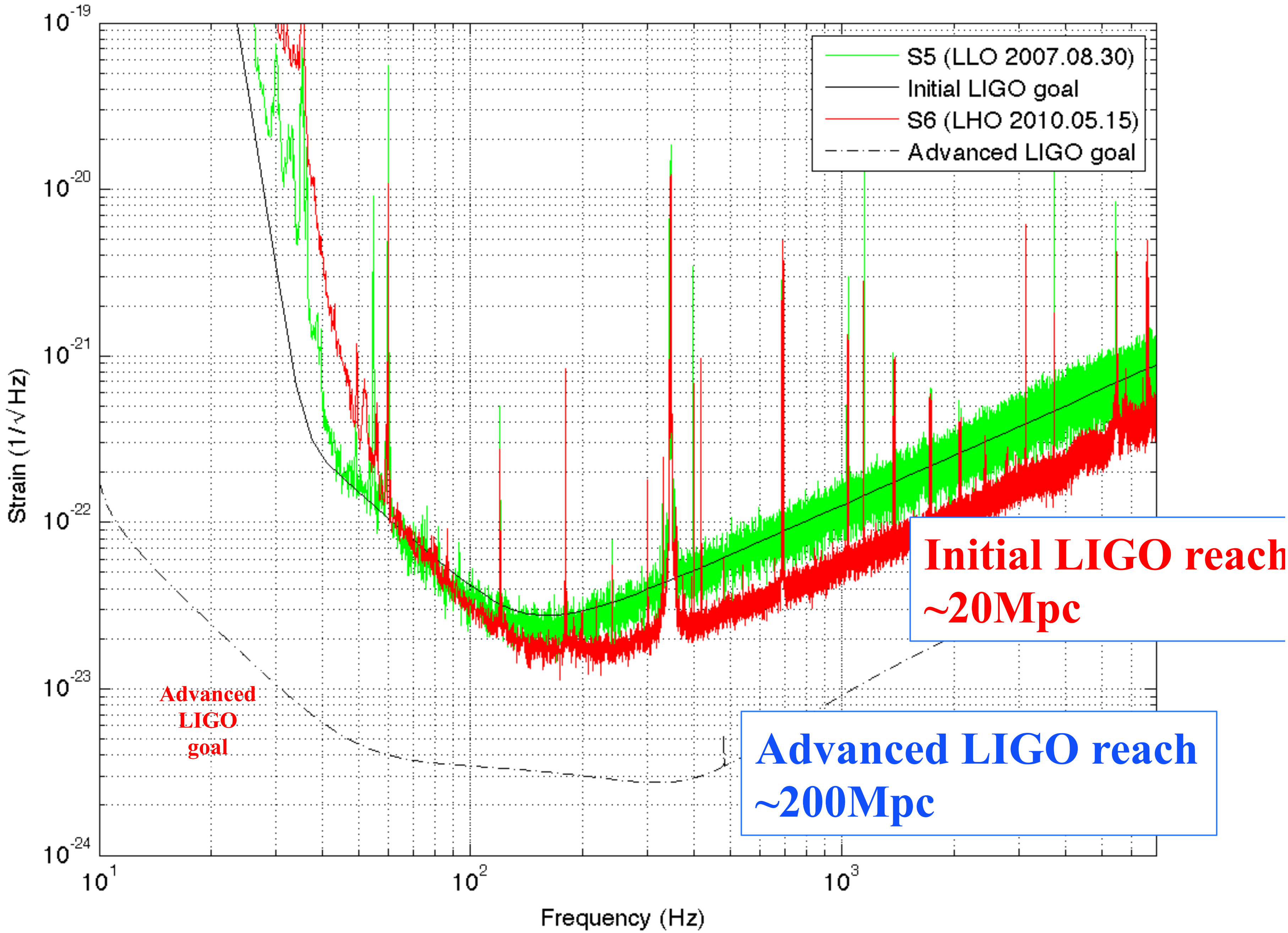
- Predicted by Einstein's theory of gravity, General Relativity, in 1916
- Generated by changing quadrupole moments such as in co-orbiting objects, spinning asymmetric objects
- Interact weakly with matter - even densest systems transparent to gravitational waves
- An entirely new spectrum in which to explore the universe
- Strain = Δlength/length
- GW strain at Earth ≈ 10^{-22}

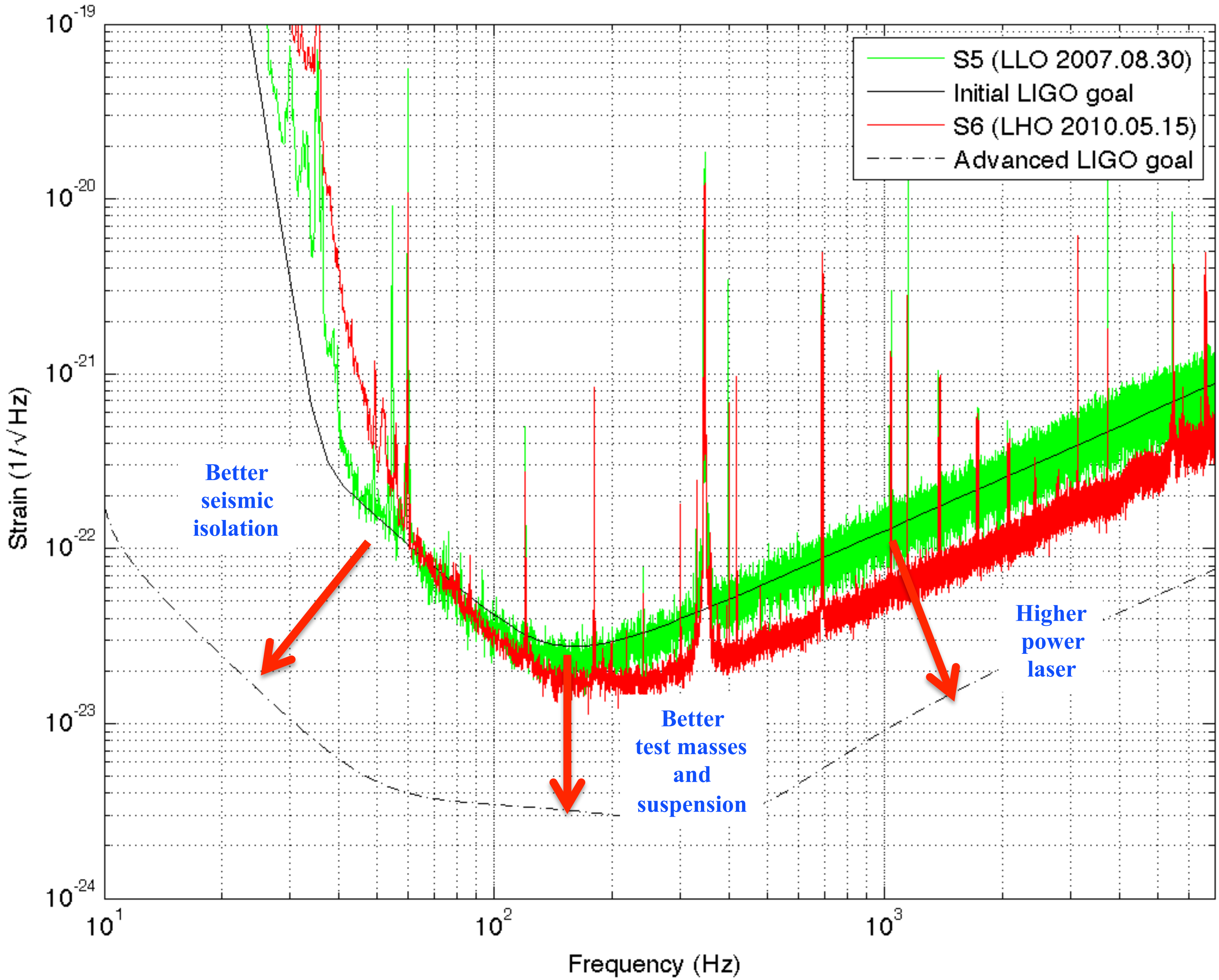


Advanced LIGO

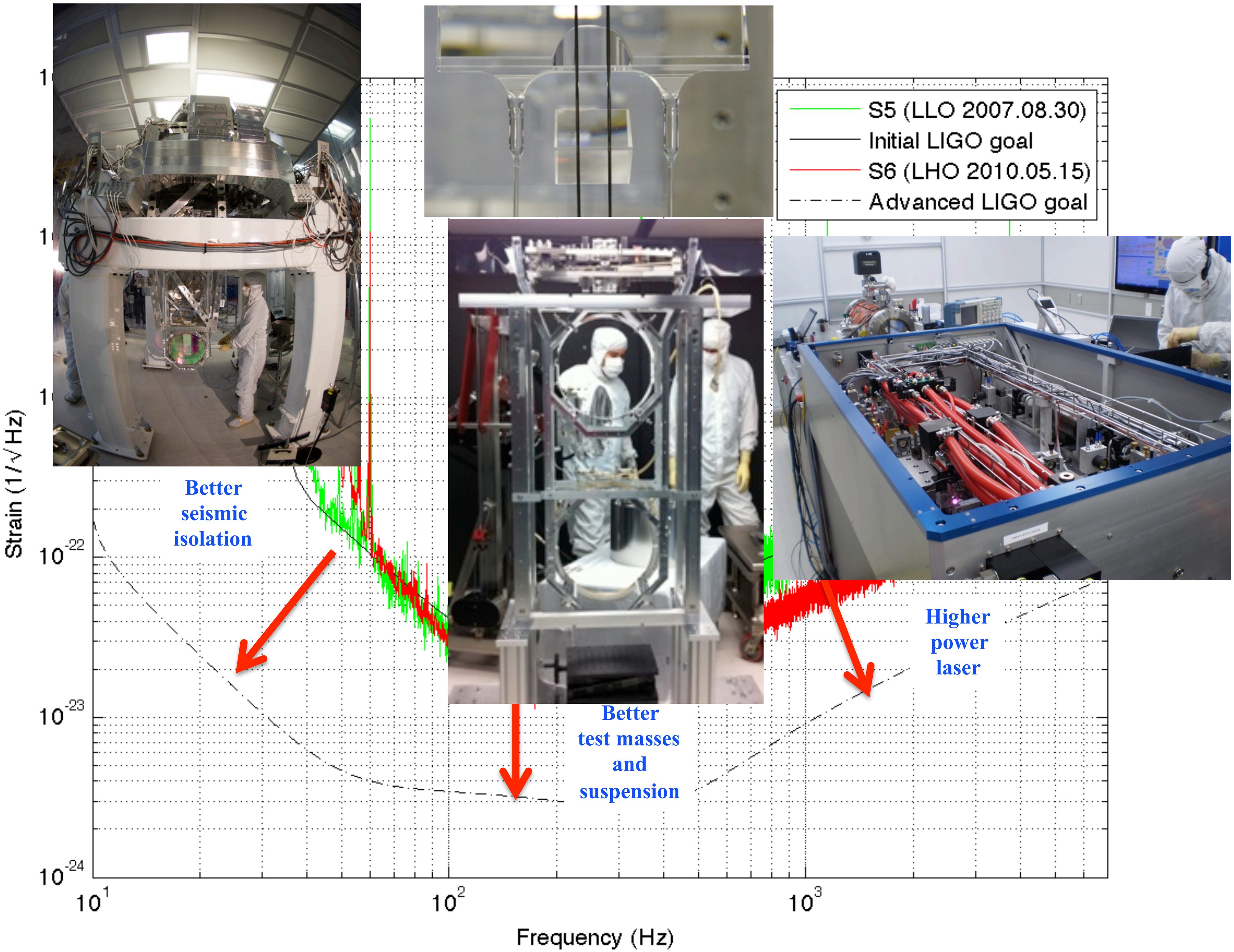
- Power recycled Fabry-Perot Michelson with Signal recycling (increase sensitivity, add tunability)
- Active seismic isolation, quadruple pendulum suspensions (seismic noise wall moves from 40Hz to 10Hz)
- DC readout, Output Mode Cleaner (better use of photons)
- ~20x higher input power (lower shot noise)
- 40 kg test masses (smaller motion due to photon pressure fluctuations)
- Larger test mass surfaces, low-mechanical -loss optical coatings (decreased mid-band thermal noise)
- Fused Silica Suspension (decreased low-frequency thermal noise)




S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Strain (1/√Hz)
Frequency (Hz)
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^1
10^2
10^3
Initial LIGO reach
~20Mpc
Advanced LIGO reach
~200Mpc
Advanced
LIGO
goal



S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Better seismic isolation
Better test masses and suspension
Higher power laser
Strain (1/√Hz)
Frequency (Hz)

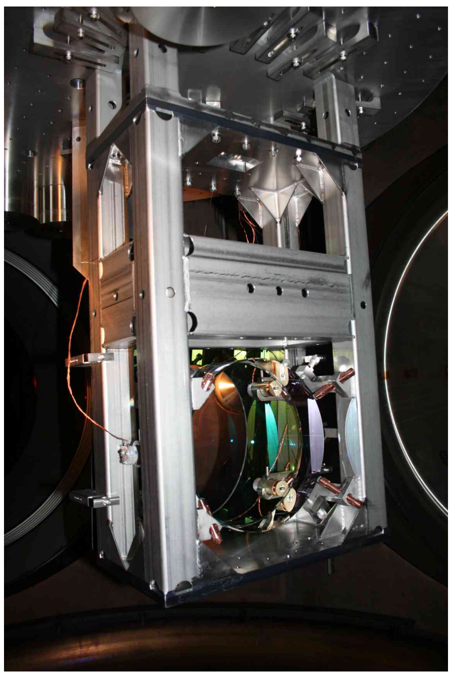


S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Strain (1/√Hz)
Frequency (Hz)
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
Better seismic isolation
Better test masses and suspension
Higher power laser

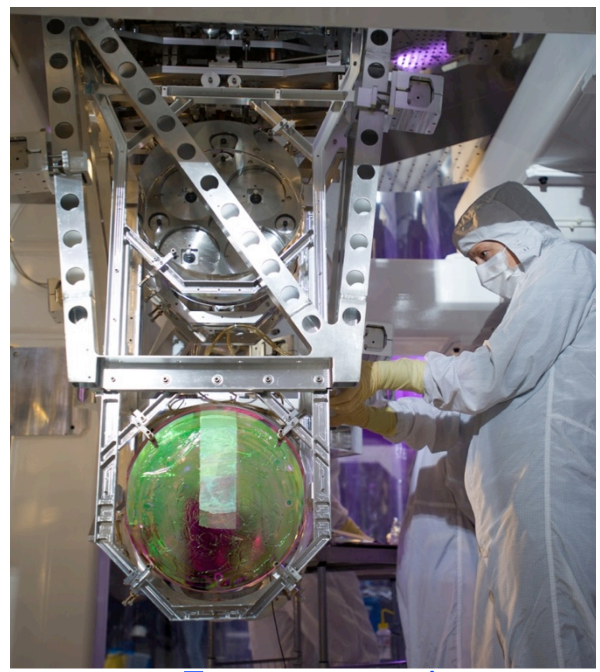
10X more sensitive, >10X harder…

- 14 unique fabricated parts
- 68 fabricated parts total
- 165 total including machined parts and hardware

- 188 unique fabricated parts
- 1569 fabricated parts total
- 3575 total including machined parts and hardware



Test mass suspension
From Initial LIGO



Test mass suspension
From Advanced LIGO

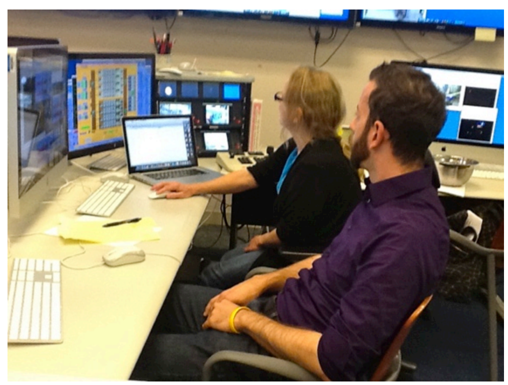
Phases

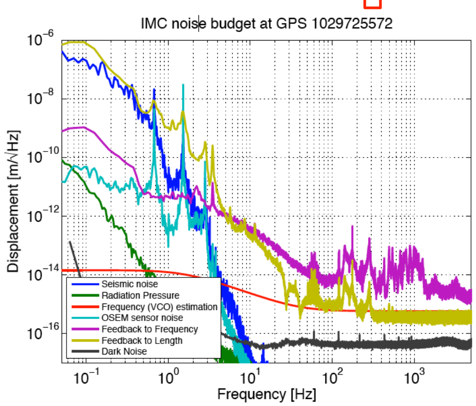
deinstall

modify vacuum

in-chamber clean

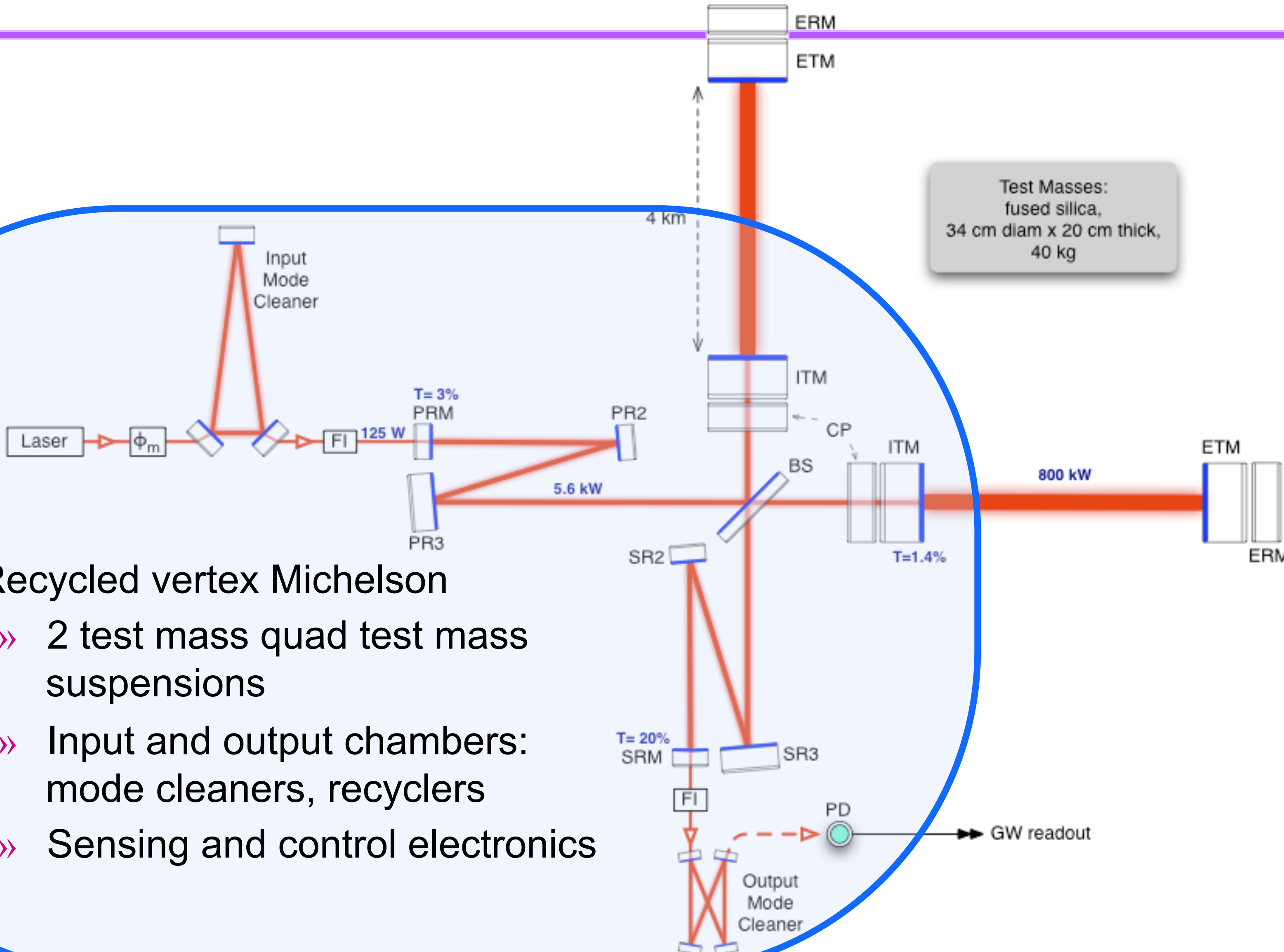
install





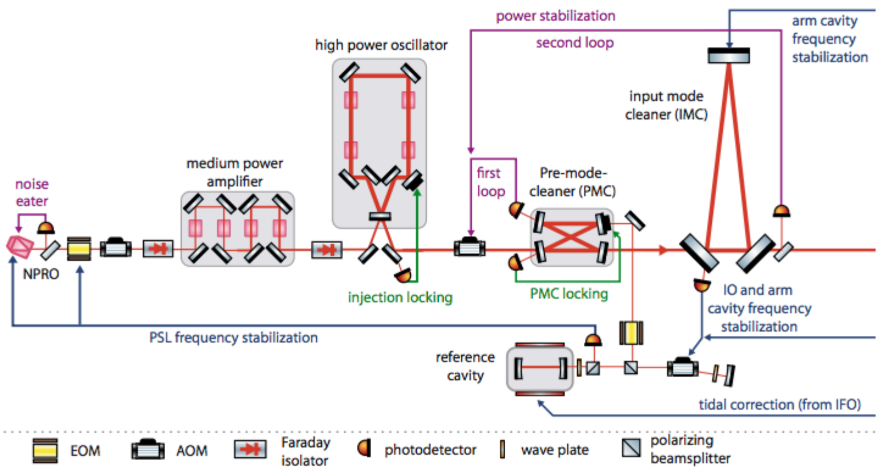
commission

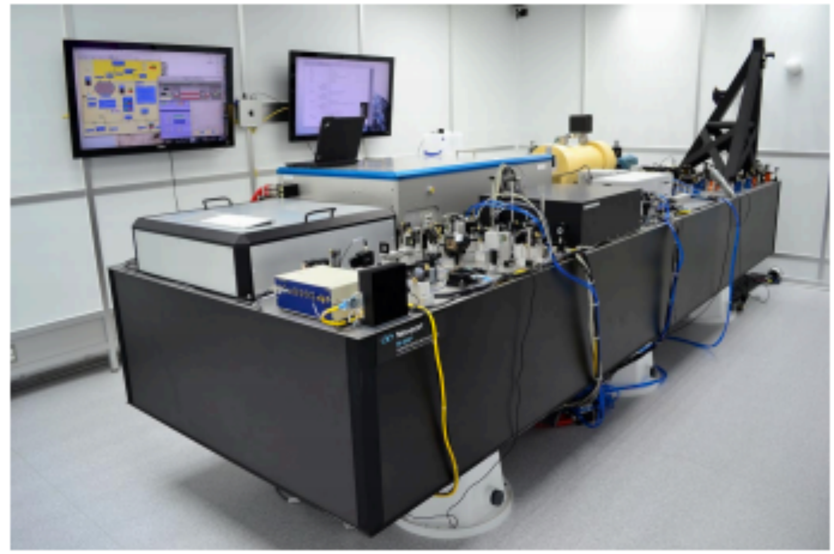
LIGO Livingston Install

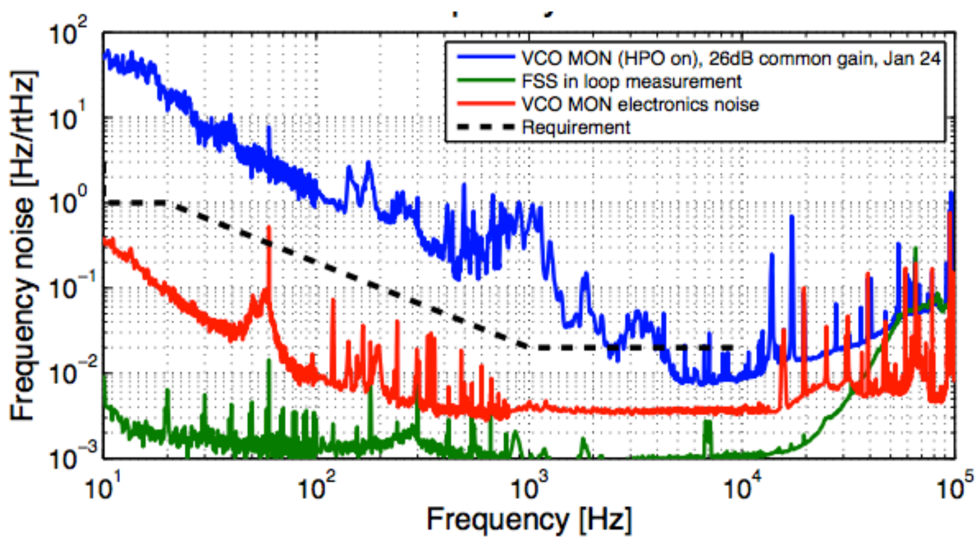


- Recycled vertex Michelson
  - 2 test mass quad test mass suspensions
  - Input and output chambers: mode cleaners, recyclers
  - Sensing and control electronics

Pre-stabilized laser

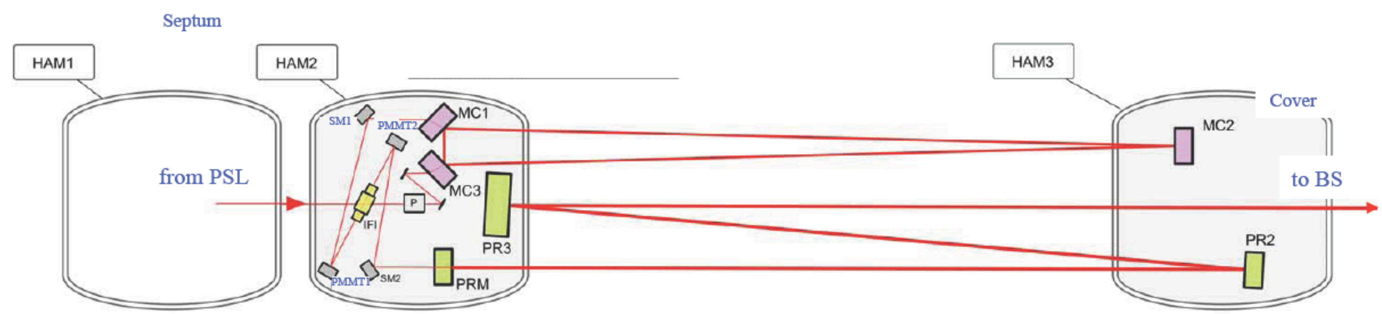


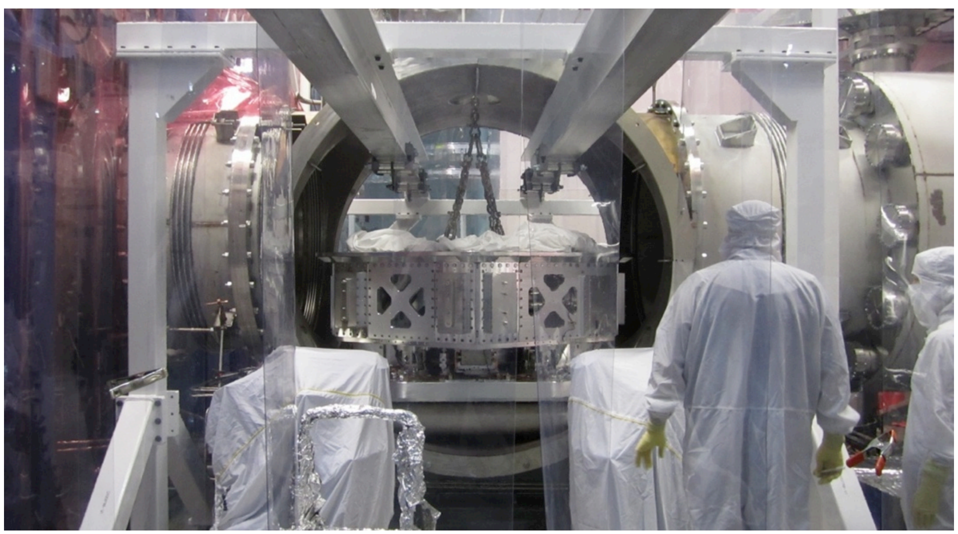


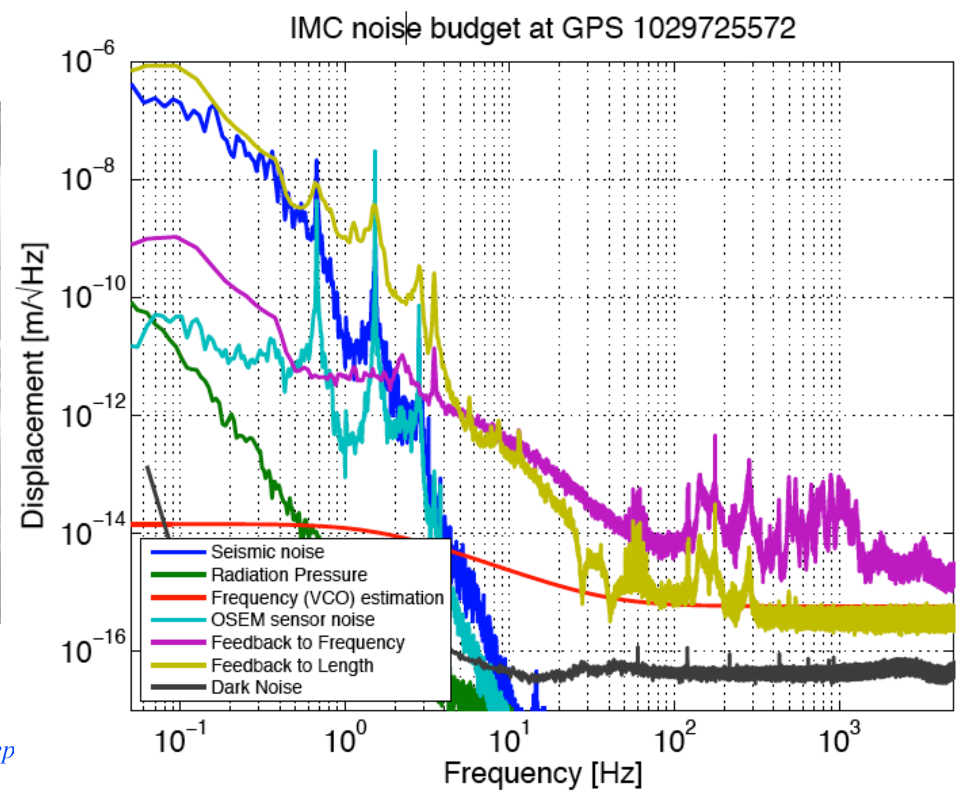


- Frequency noise measured at Livingston
- 3 W input to IMC
- noise between 10 and 100 Hz is already better; expect to meet spec without difficulty

LIGO Livingston input mode cleaner

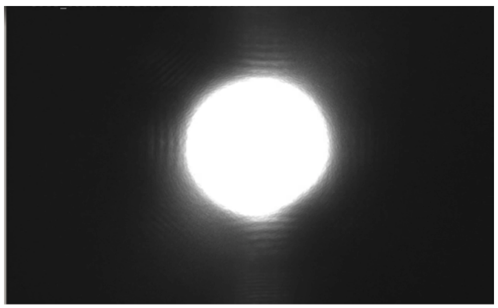




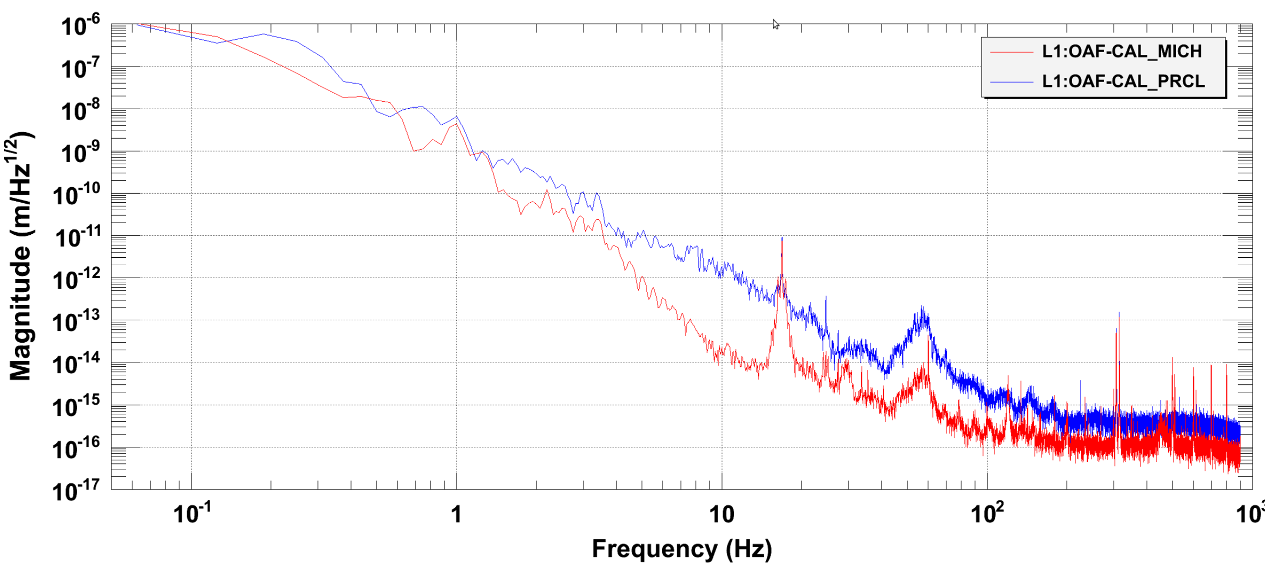


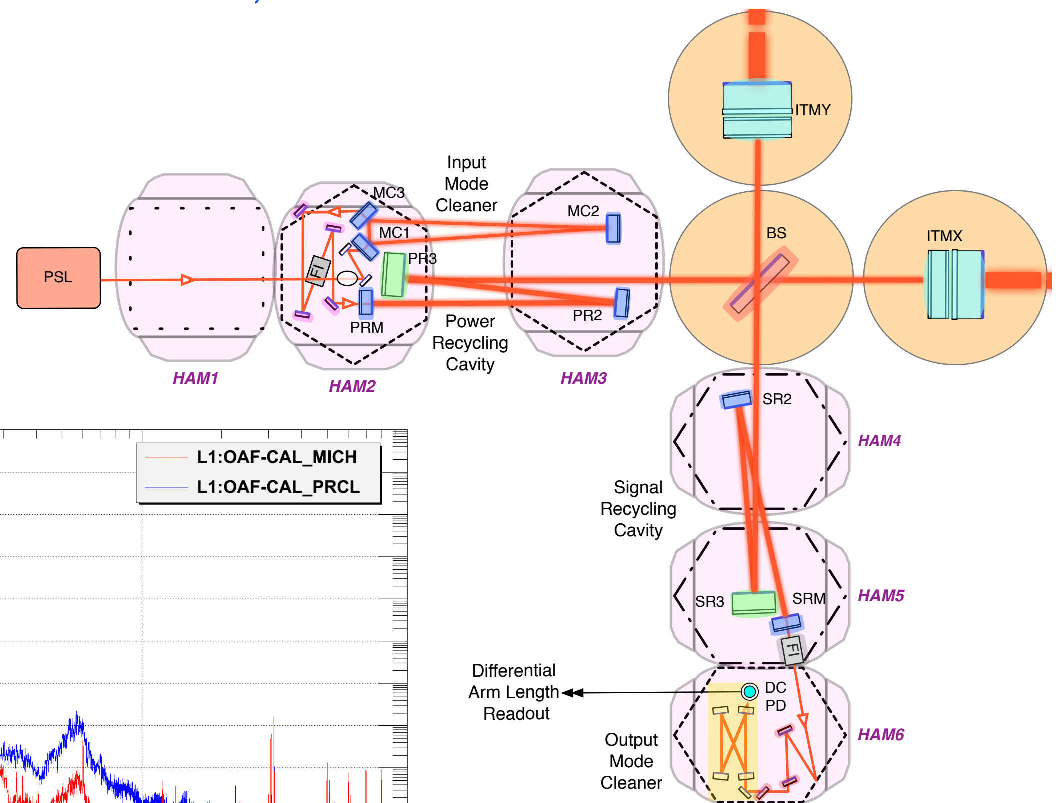
Livingston DRMI

- Dual-recycled Michelson Interferometer (‘***DRMI***’)
  - » Nearly all parts in place for this stage: currently vented for additional components
  - » Power recycled Michelson locked on DC readout, calibrated

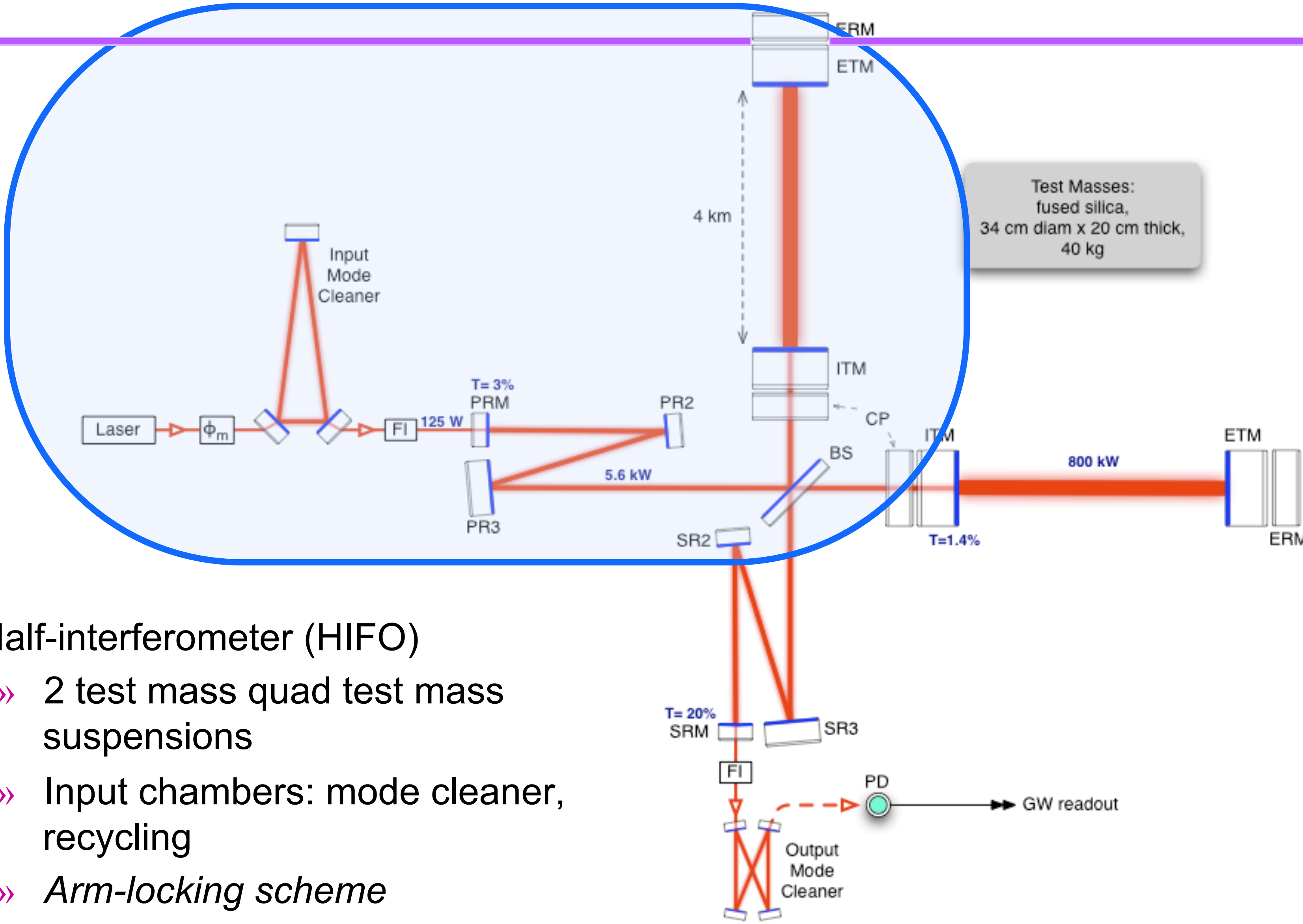


Light transmitted past the output mode cleaner





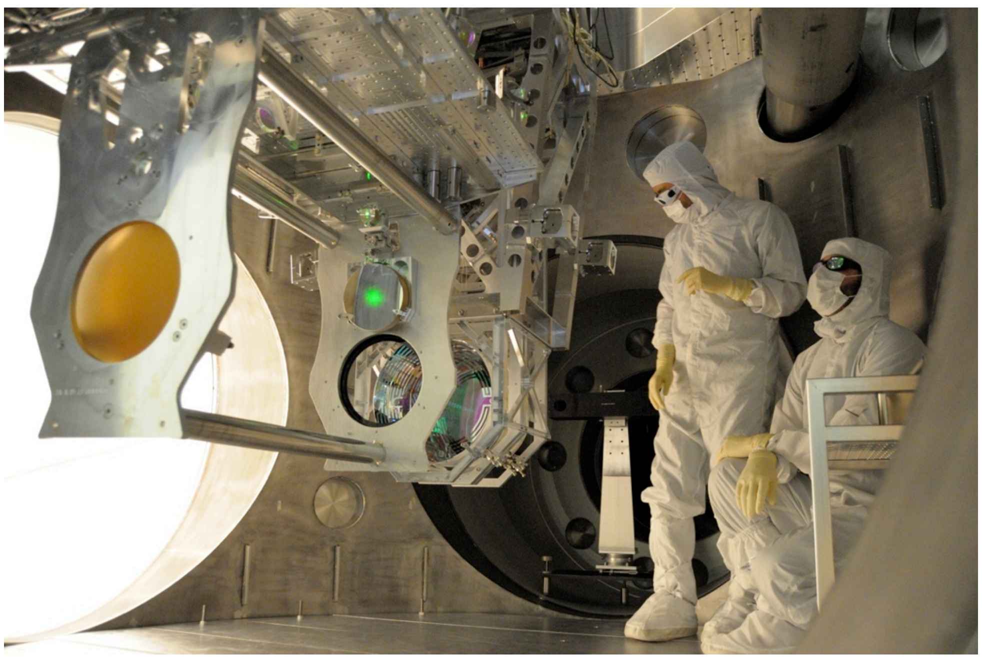
LIGO Hanford Install

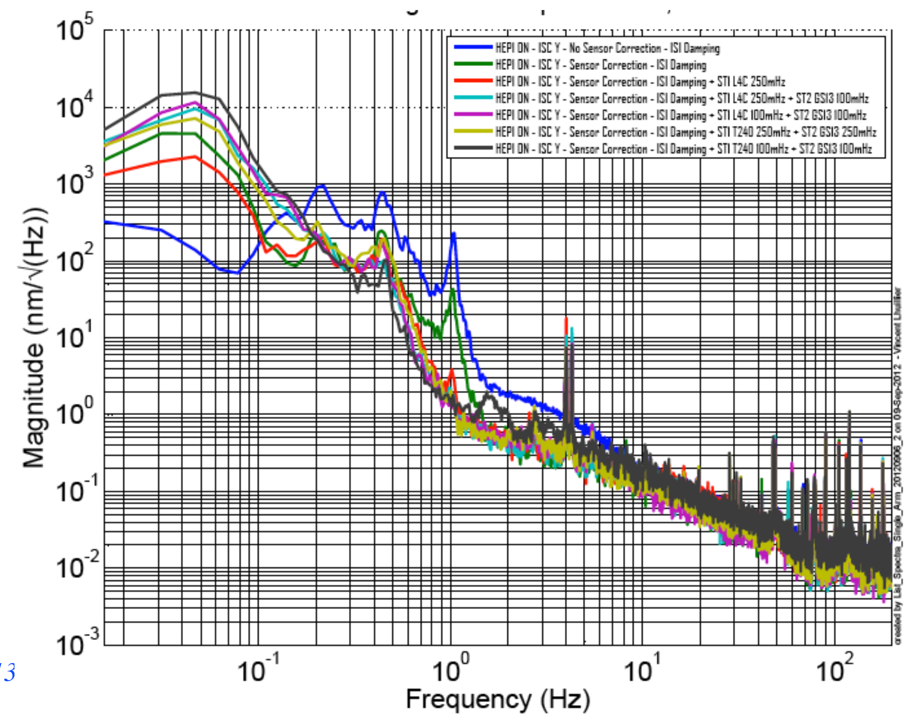


- Half-interferometer (HIFO)
  - 2 test mass quad test mass suspensions
  - Input chambers: mode cleaner, recycling
  - *Arm-locking scheme*

Hanford single-arm integration

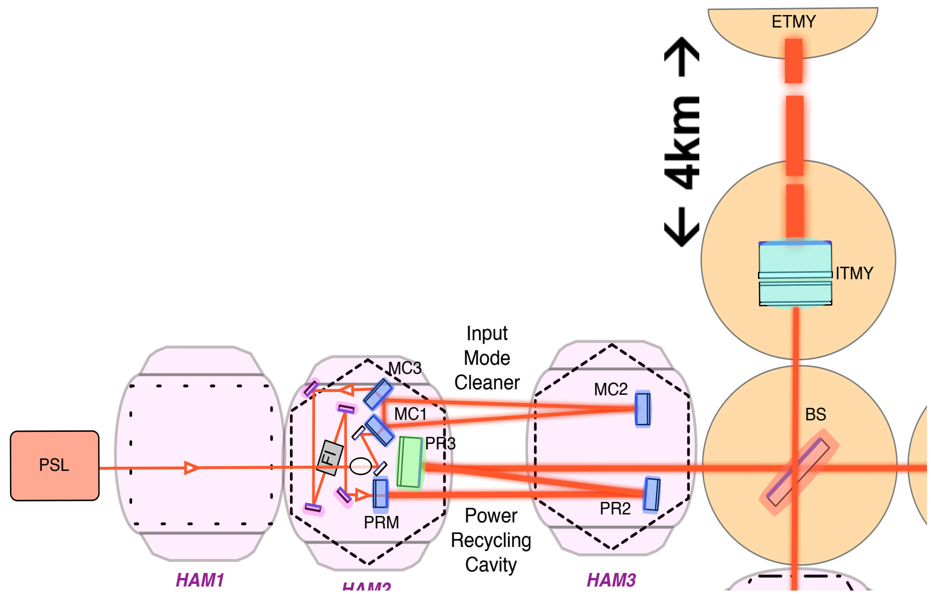
- **New lock acquisition strategy developed for Advanced LIGO**
  - **Arm Length Stabilization system controls each arm cavity, putting them off-resonance**
  - **The 3 vertex lengths are controlled using robust RF signals**
  - **Arm cavities are brought into resonance in a controlled fashion**
- ***Therefore, commissioned single 4km arm***

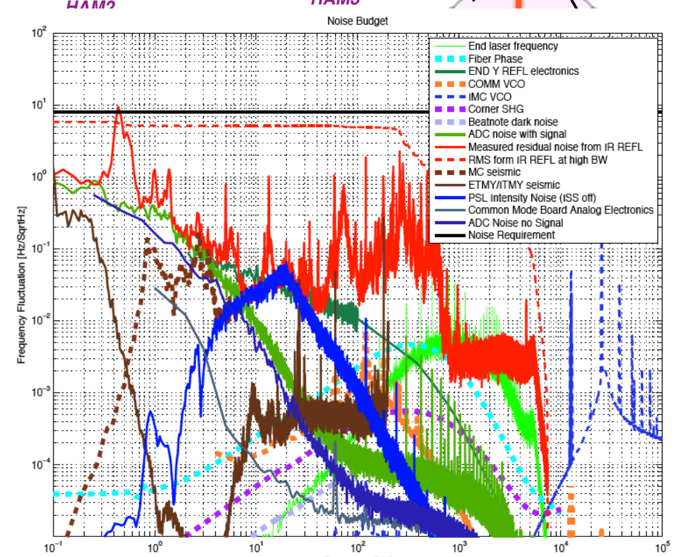




Hanford HIFO-Y

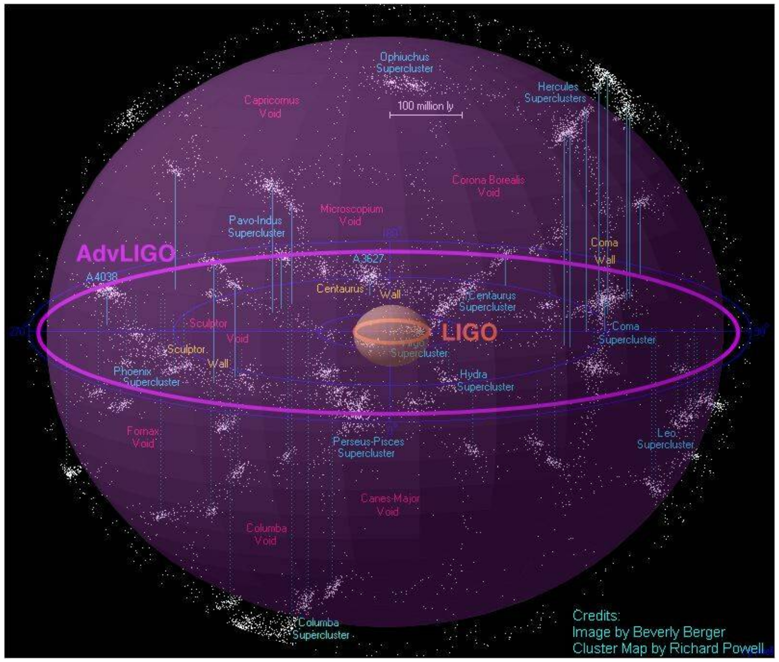
- Half-Interferometer (*'**HIFO**'*)–Y arm
  - » Green light demonstrated to allow a continuous controlled positioning of cavity
  - » Fluctuations of the HIFO-Y length ~5 Hz RMS (meets noise requirement of 8Hz)
  - » May require acoustic mitigation (in-air periscopes in corner and table motion) and modified suspension control filters for known mechanical modes





Science

See E. Thrane's talk (today) and L. Price's (Thu) for more prospects on detection



Binary neutron stars

- Initial LIGO reach: 15Mpc; rate ~ 1/50yrs
- Advanced LIGO ~ 200Mpc
- 'Realistic' rate ~ 40 events/yr

Rates paper: Class. Quant. Grav, 27 (2010) 173001

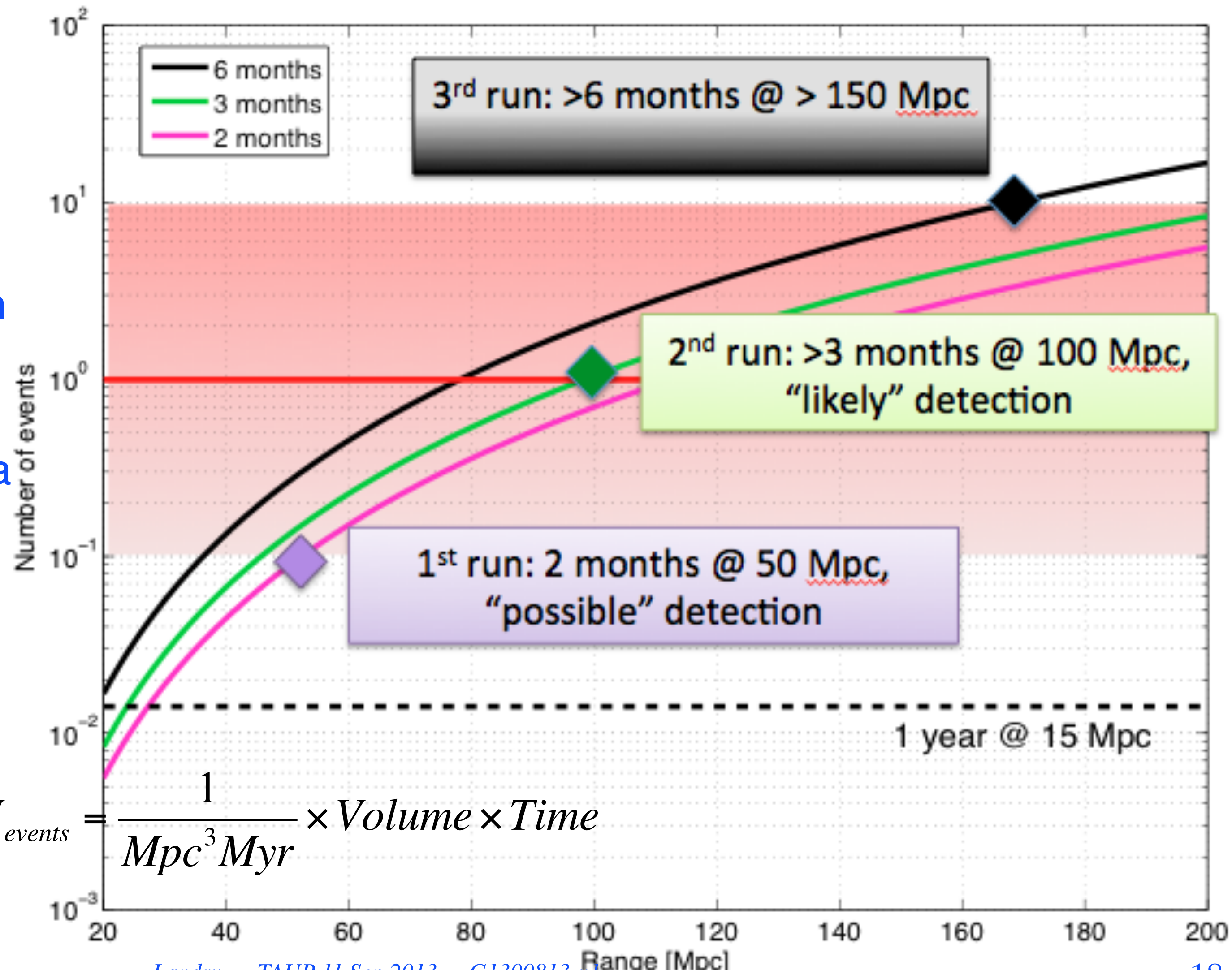
Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}	$\dot{N}_{\rm max}$ yr^{-1}
	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
Initial	BH–BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			<0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
Advanced	BH–BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

Current guess for sensitivity evolution, observation

- Vertical scale is the number of binary inspirals detected
- Rates based on population synthesis, realistic but uncertain
- LIGO Scientific Collaboration (LSC) preparing for the data analysis challenge
- Close collaboration with Virgo
- Early detection looks feasible

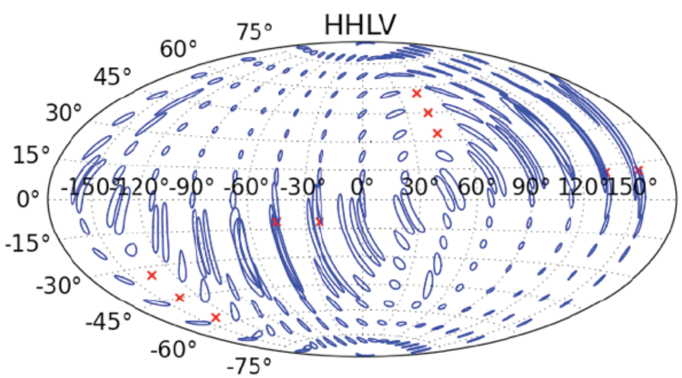
- [arXiv:1304.0670, arXiv:1003.2480]()



$$N_{events} = \frac{1}{Mpc^3 Myr} \times Volume \times Time$$

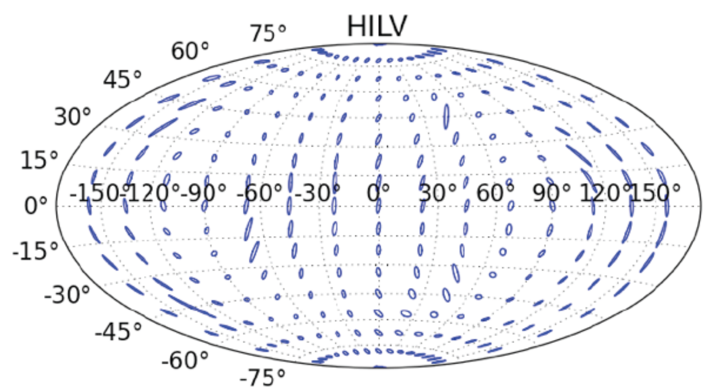
LIGO India

- Compelling science case for an interferometer outside the plane of existing detectors
- LIGO Lab, LSC to send components of third interferometer (second at Hanford) to India
- Currently reviewing installation planning – must complete assembly, store components, later, send to India



Red crosses denote regions where the network has blind spots

Fairhurst 2011



Fairhurst 2011

Summary

- Installation and integration phases interleaved until early 2014, followed by extended commissioning to late 2014: acceptance of Advanced LIGO interferometers
- First science runs, at reduced sensitivity expected in 2015 and 2016
- Anticipate regular detections before the decade is out